UCONN-95-06

Probing Nucleon Structure via High Energy Elastic Scattering†

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Abstract

Analyses of high energy elastic pp and $\bar{p}p$ scattering data from CERN ISR and SPS Collider seem to provide strong evidence in favor of the gauged nonlinear σ-model of the nucleon. This model describes the nucleon as a topological soliton and introduces the vector mesons ω, ρ, a_1 as gauge bosons. The model, however, needs to be extended to include an explicit quark sector, where left and right quarks interact via a scalar field. A critical behavior of the scalar field results in a phase transition to a condensed quark-antiquark ground state. The latter can provide the outer cloud of the nucleon, which is responsible for diffraction scattering. If the nucleon is probed deeper via high energy elastic scattering, then evidence for the phase transition may emerge from a rapid change in the behavior of $d\sigma/dt$.

†Talk given at the VIth Blois Workshop on Elastic and Diffractive Scattering (Blois, France, June 1995).

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Following the birth of the quark model in the mid-sixties, physicists have devoted a great deal of effort to determine the composite structure of the nucleon. This has not led to a unique description of the nucleon. Instead, it has generated a wide array of models, such as: constituent quark model, MIT bag model, topological soliton model, non-topological soliton model, color dielectric model, etc. The reason for such a proliferation of nucleon models is not hard to see. Low energy properties of the nucleon and low energy nucleon-nucleon interaction have not been able to single out one model as incorporating the key features. What I am going to present is that, surprisingly, there seems to be strong evidence in favor of one of the models — namely, the gauged nonlinear σ-model that describes the nucleon as a topological soliton and introduces the vector mesons ω, ρ, a_1 as gauge bosons[1)]. The model, of course, needs to be extended to include explicitly a quark sector, where left and right quarks interact via a scalar field and form a condensed $q\bar{q}$ ground state (a chiral condensate). The nucleon emerges as a topological soliton embedded in this condensate.

Let us first see how high energy elastic pp, $\bar{p}p$ scattering gets linked to the low energy soliton model in our work. High energy elastic pp and $\bar{p}p$ scattering have been measured at the CERN ISR and SPS Collider over a wide range of energy: $\sqrt{s} = 23 - 630$ GeV. These data have been analyzed by me and my collaborators over a number of years[2−4)]. From our analyses, we arrived at the following phenomenological description. The nucleon has an inner core and an outer cloud. Elastic scattering at high energy is primarily due to two processes: (1) a glancing collision in which the outer cloud of one nucleon interacts with that of the other giving rise to diffraction scattering; (2) a hard collision in which one nucleon core scatters off the other nucleon core via vector meson ω exchange, while their outer clouds overlap and interact independently. In the small momentum transfer region, diffraction dominates. As the momentum transfer increases, the hard scattering takes over. In Fig.1, we show our fit to the ISR elastic pp data at $\sqrt{s} = 53\,\mathrm{GeV}$[4)]. Solid curve represents the calculated differential cross section. The dot-dashed curve represents the differential cross section due to diffraction alone, and the dashed curve represents the differential cross section due to hard scattering alone. As can be seen, diffraction dominates in the forward direction, while the hard scattering takes over as $|t|$ increases. The fits we obtained showed that our phenomenological model of the nucleon does provide a satisfactory description of high energy elastic scattering. Furthermore, questions such as ω behaving as a spin-1 boson in our analyses can be answered as due to the topological nature of the baryonic charge[5)].

Despite these encouraging developments, we face a major problem at this point. Several groups have found that the gauged nonlinear σ-model, even though quite successful in describing the low energy properties of the nucleon, consistently predicts too large a soliton mass ($\sim 1500\,\mathrm{MeV}$) compared to the actual mass of the nucleon ($939\,\mathrm{MeV}$)[6)]. To address this question, let us consider the Lagrangian density of the Gell-Mann-Levy σ-model :

$$\begin{aligned}\mathcal{L} = &\bar{\psi} i \gamma^\mu \partial_\mu \psi + \frac{1}{2}\left(\partial_\mu \sigma\, \partial^\mu \sigma + \partial_\mu \vec{\pi} \cdot \partial^\mu \vec{\pi}\right) - G \bar{\psi}\left(\sigma + i\gamma^5 \vec{\tau}\cdot\vec{\pi}\right)\psi \\ &-\lambda\left(\sigma^2 + \vec{\pi}^2 - f_\pi^2\right)^2, \qquad (1)\end{aligned}$$

Let us write, $\sigma + i\vec{\tau}\cdot\vec{\pi} = \zeta(x)\; U(x)$, where $U(x) = \exp\left[i\vec{\tau}\cdot\vec{\varphi}(x)/f_\pi\right]$, $\vec{\varphi}(x)$ is the Goldstone pion field and $f_\pi$is the pion decay constant ; $\zeta(x)$ is a scalar field which corresponds to the magnitude of $(\sigma, \vec{\pi})$ field: $\zeta^2(x) = \sigma^2(x) + \vec{\pi}^2(x)$. We can express the Lagrangian density (1) in terms of the left and right fields $\psi_L = \frac{1}{2}\left(1-\gamma^5\right)\psi$ and $\psi_R = \frac{1}{2}\left(1+\gamma^5\right)\psi$:

$$
\begin{aligned}
\mathcal{L} = &\bar{\psi}_L i\gamma^\mu \partial_\mu \psi_L + \bar{\psi}_R i\gamma^\mu \partial_\mu \psi_R + \frac{1}{4}\zeta^2 tr[\partial_\mu U \partial^\mu U^\dagger] + \frac{1}{2}\partial_\mu \zeta \partial^\mu \zeta \\
&-G\zeta \left[\bar{\psi}_L U \psi_R + \bar{\psi}_R U^\dagger \psi_L\right] - \lambda \left(\zeta^2 - f_\pi^2\right)^2 . \qquad (2)
\end{aligned}
$$

This model can now be easily gauged by replacing the ordinary derivatives by the covariant derivatives. Using the path-integral formalism, one then brings in a new piece of action—the Wess-Zumino-Witten action. Two additional assumptions are made in the gauged nonlinear σ-model : (1) all the important interactions are in the meson sector (that is, among π, ω, ρ and a_1), and not in the fermion sector ; (2) the scalar field $\zeta(x)$ can be replaced by its vacuum value f_π from the very beginning (this makes the model nonlinear). Consequently, what one really has in the nonlinear σ-model, is a soliton surrounded by a noninteracting Dirac sea [Fig.2a]. If, instead, we consider the linear σ-model, then the scalar field $\zeta(x)$ provides an interaction between the left and right quarks, and we have an interacting Dirac sea surrounding the soliton [Fig.2b]. One finds that, if the scalar field has a critical behavior, and by this, I mean, it is zero at small distances, but rises sharply at some distance $r = R$ to its vacuum value f_π [Fig.2c], then the energy of the interacting Dirac sea can be significantly less than that of the noninteracting Dirac sea. The system, in that case, makes a phase transition to the interacting ground state and reduces its total energy by the condensation energy[7)]. This can solve the large soliton mass problem of the σ-model. Furthermore, the condensed ground state of the left and right quarks is analogous to a superconducting ground state. A number of important consequences follow from this result[8)]. One of them is that the condensed $q\bar{q}$ ground state can provide the outer cloud of the nucleon that we have in the phenomenological description of elastic scattering.

We may now ask : Is there any indication of the phase transition considered above. The answer is : perhaps. Let us examine this point. In elastic scattering, when the momentum transfer is Q, we are probing the interaction at an impact parameter, i.e., at a transverse distance of the order of Q^{-1}. Let us say the critical distance R in Fig.2c is $0.07\,F = (3\,\text{GeV})^{-1}$. (The reason for choosing this particular value is pointed out later.) If we now consider elastic scattering with $Q > 3\,\text{GeV}$, then each nucleon probes the other nucleon at an impact parameter less than R, i.e., in a region where the scalar field $\zeta(r)$ is zero, the quarks are massless, and we are in the perturbative QCD regime. Elastic scattering in perturbative QCD has been studied by Sotiropoulos and Sterman[9,10)]. The scattering originates from a valence quark in one nucleon scattering off a valence quark in the other nucleon, and the differential cross section behaves as

$$
\frac{d\sigma}{dt} \sim \frac{d\sigma_{qq}}{dt} \left(\frac{1/Q^2}{R_p^2}\right)^8 . \qquad (3)
$$

The last factor in (3) arises from the requirement that each spectator valence quark has to be within a transverse distance of $1/Q$ of the colliding valence quark[9)]. The valence quark-quark scattering in (3) is assumed to be due to a color singlet amplitude behaving as t^{-1}, so that $d\sigma_{qq}/dt \sim t^{-2}$. For $|t| > 9$ GeV^2, this leads to the power fall-off behavior[10)]

$$
\frac{d\sigma}{dt} \sim \frac{1}{t^{10}} , \qquad (4)
$$

which corresponds to the dimensional counting rule.

The behavior (4) is very different from the Orear fall-off that we obtain for $Q < 3$ GeV ($|t| < 9$ GeV^2) due to ω exchange:

$$\frac{d\sigma}{dt} \sim e^{-a\sqrt{|t|}}. \tag{5}$$

The length scale a is connected with the finite size of the solitons. The behavior (5) originates from a region where the scalar field $\zeta(r)$ has a nonvanishing value f_π, the quarks and antiquarks form a condensed ground state, and we are in a nonperturbative regime. So a rapid change in the behavior of $d\sigma/dt$ from an exponential fall-off to a power fall-off will signal a transition from a nonperturbative phase, where $\zeta(r) = f_\pi$, to a perturbative phase, where $\zeta(r) = 0$. Interestingly enough, the ISR $\sqrt{s} = 53\,\mathrm{GeV}$ data indicate a change in the behavior of the differential cross section for $|t| \simeq 9\,\mathrm{GeV}^2$. As can be seen from Fig.1, the last three data points show a flattening of the differential cross section. (Our earlier choice of $R = (3\,\mathrm{GeV})^{-1}$ is, in fact, based on this observation.) The above scenario also implies that the valence quarks are contained in a small region of size R at the center of the nucleon, so that when $Q < R^{-1}$ ($|t| < 9\,\mathrm{GeV}^2$), we see soliton-soliton scattering, but when $Q > R^{-1}$ ($|t| > 9\,\mathrm{GeV}^2$), the elastic scattering originates from valence quark-quark scattering. We note that before the perturbative QCD behavior t^{-10} sets in, there can be an intermediate behavior ($d\sigma/dt \sim t^{-8}$) preceding it. The latter behavior occurs when the three valence quarks from one nucleon independently scatter off the three valence quarks from the other nucleon—a mechanism known as the Landshoff mechanism[11)].

In conclusion, our investigation of high energy pp and $\bar{p}p$ scattering strongly indicates that the nucleon is a soliton that arises from the topological baryonic charge distribution[5)]. The latter is probed by ω, which acts like a photon. The soliton is embedded in a condensed ground state of chiral quarks and antiquarks. A rapid change in the behavior of the elastic differential cross section from an exponential fall-off to a power fall-off at a large value of $|t|$ ($\sim 9\,\mathrm{GeV}^2$) will signal a QCD chiral phase transition from a nonperturbative to a perturbative regime. Precise systematic measurements of the large $|t|$ pp and $\bar{p}p$ elastic differential cross sections at the Tevatron, RHIC[12)], and LHC[13)] may reveal such a change in the behavior of $d\sigma/dt$. It seems very exciting that from high energy elastic scattering, we may find evidence of a chiral phase transition and of valence quarks being confined at the center of the nucleon in a small region of size about one-tenth of a Fermi.

This work is supported in part by the U.S. Dept. of Energy.

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11. Landshoff originally assumed exchanges of three gluons. Sotiropoulos and Sterman point out that this process has to be three color singlet exchanges (Ref.10).
12. At present, there is an approved pp elastic scattering experiment at RHIC, which will measure $d\sigma/dt$ in the region $|t| = 0{-}1.5\ \mathrm{GeV}^2$. See W.Guryn's contribution to this workshop.
13. The possibility of doing $\bar{p}p$ elastic scattering at the LHC is discussed by K. Eggert in Proceedings of this workshop.

Fig. 1. Solid curve is the calculated cross section (see text for details).